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EXPLOSIBILITY OF COAL DUST FROM FOUR MINES IN UTAH

BY

H. P. GREENWALD

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PREFACE

The Bureau of Mines, in its investigations of the prevention of mine explosions, studies the relative hazard of explosion in typical coal mines in different parts of the country. The results of some of these explosion-hazard investigations have already been given in Bulletin 167[1] and others will be discussed in Bulletin 268, now in press.

After the disastrous explosion which killed 172 men at the Castlegate mine in Utah on March 8, 1924, the question arose of the adequacy of the preventive methods used in that district. The Bureau of Mines had not then tested the explosibility of coal dust from beds mined in Utah. One reason for this was that the bureau had no funds to defray the cost of transporting 2,000 miles to the bureau's experimental mine near Pittsburgh, Pa., the large amounts of coal required for test. Because of the question as to preventive methods it seemed desirable to make tests to determine whether the Utah coal dust was more explosive because of its high content of volatile combustible, including resinous matter, than dusts tested from eastern mines, and whether the percentages of rock dust found necessary by tests of eastern coals would be adequate for Utah mines. The Federal Government, aside from its general interest in mine safety, has a proprietary interest in the question, as vast reserves of similar coals on the public domain in Utah and Wyoming are being opened to mining under the Federal leasing system.

Before the explosion disaster at Castlegate, rock-dusting had not been used in Utah mines, but watering had been employed since the Winterquarters mine disaster in 1900, which killed 200 men. The watering was perhaps done more systematically than in mines in any other part of the country. State regulations required water lines to be laid to the face of all workings and the workings to be washed down regularly. Although there had been some small explosions between the Winterquarters and the Castlegate disasters, none had been serious enough to shake the confidence of the Utah mining officials in the efficacy of the watering method.

In the mines of the Book Cliffs field the conditions that affect explosion hazards are severe, possibly worse than in any other

[1] Rice, G. S., Jones, L. M., Egy, W. L., and Greenwald, H. P., Coal-Dust Explosion Tests in the Experimental Mine, 1913 to 1918, Inclusive: Bull. 167, Bureau of Mines, 1922, 639 pp.

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coal-mining district in the country. The principal bed mined is 7 to 24 feet thick and is high-volatile coal, virtually free from partings carrying impurities. The roof in most of the workings is strong massive sandstone, sandy shale, or coal, and the floor is hard sandstone or shale. Hence impurities do not get mixed with the coal to any extent in mining and loading. Usually in the entries a coal roof is left, and any coal that falls from the roof or ribs or drops from cars is ground to dust on the hard floor. It has been the common practice to pile the cars high above the sides with coal, resulting in much coal being spilled along the roadways, where it is ground under the wheels. As the coal is clean, this road dust is almost pure coal and is very explosive. Watering tends to lay the dust, but, as is well known, it is extremely difficult to keep coal dust wet in a region of naturally dry air where ventilation currents evaporate the water and continually carry out large amounts as vapor.

After the Castlegate explosion the State officials conferred with the mine operators and then issued special orders which required rock-dusting in the intake roads, the use of water on the cutter bars of machines in the faces, and the washing down of faces by hose. As a result of watering at the face, the air in the returns is humid and tends to moisten rock dust so that it will not rise in a cloud if an explosion occurs. For protecting the returns the State requires the use of rock-dust barriers.

On the main intake roads the ribs and any timbers present are generally well rock-dusted, but the floor, especially between the rails, becomes covered with coal dust so rapidly that spraying the floor from tank cars was tried, although dry rock dust had been applied to the ribs and sides of the entry.

In addition to the dust hazard, another factor of danger in the Castlegate district is that fire damp is encountered as the mine workings extend farther below the surface. Small percentages of fire damp increase the explosibility of dust mixtures, and it was desirable to determine the effects on Utah coal-dust and rock-dust mixtures.

The mine operators desired to know the adequacy of the methods being employed for preventing explosions, as well as the relative explosibility of their dust, so a railroad car was carefully loaded with coal samples from four typical mines. This coal was furnished and sent to the Bureau of Mines jointly by certain operators and the tests described in this paper were made with the dusts ground from the four large samples.

On account of the wide interest among western coal operators in the results of these tests and the fact that the results may have

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a general application to conditions in other mines in Utah and Wyoming, including mines that may be opened on Government lands, publication of the main facts learned is deemed advisable. Although coals from only four mines were tested, the mines chosen for test are widely separated, but have much the same natural conditions, and are believed to be representative of general conditions in the Book Cliffs field.

As the purpose of the tests did not include publication of names, the names of the mines and the companies operating the mines are withheld. As the bureau has no mandatory powers—these lie wholly in the State—the information gathered has been regarded as confidential. The operators concerned heartily cooperated in the investigation, they furnished large samples of coal and bore the cost of transportation to Pittsburgh, and they have been given detailed reports on the relative explosion hazard of their respective mines.

The testing work was in charge of H. P. Greenwald, assistant physicist, assisted by H. C. Howarth, superintendent of the experimental mine; and was under the general planning and supervision of J. W. Paul, then chief of coal-mine investigations, and the undersigned.

George S. Rice,
Chief Mining Engineer.

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EXPLOSIBILITY OF COAL DUST FROM FOUR MINES IN UTAH

By H. P. Greenwald

INTRODUCTION

During March, 1925, G. S. Rice, chief mining engineer, and J. W. Paul, then chief of coal-mining investigations, of the Bureau of Mines, while visiting a number of mines in Carbon County, Utah, arranged with the operators of four mines to ship 5-ton samples of run-of-mine coal to the bureau's experimental mine for tests of the explosibility of the coal dust. B. W. Dyer, then district mining supervisor, arranged for the collection and shipment of the samples, which arrived at the experimental mine near Bruceton, Pa., on April 13 and were immediately prepared for testing. The first test was made on April 17, the last of the 57 made was completed on July 10, and six weeks more passed before the computation and writing of the test records ended.

This report describes the methods of test and summarizes the results of all the tests, but does not take up the application of the test results to the conditions existing at any particular mine. Separate explosion-hazard reports that apply the figures from this report to specific conditions have been prepared for the operators of each of the four mines that supplied the coal.

ACKNOWLEDGMENTS

Acknowledgment is made of the hearty cooperation of the officials of the four companies from whose mines the samples came and who financed their transportation to the experimental mine. Without such cooperation the bureau would be seriously handicapped in its effort to determine the explosibility of dust from coals mined in the United States, and the conditions necessary to safety would remain largely a matter of speculation.

COALS TESTED

The four coals tested are designated in the present report as *A*, *B*, *C*, and *D*. The proximate analysis of a coal ordinarily has been

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used in correlating the explosibility of various coals. The average proximate analyses of the coal dusts as prepared for the tests are as follows:

Analyses of coals tested, per cent

	Designation			
	A	*B*	*C*	*D*
Moisture	4.6	2.7	2.6	5.7
Volatile matter	42.2	40.9	38.9	41.7
Fixed carbon	46.7	44.5	47.8	47.3
Ash	6.5	11.9	10.7	5.3
Ash plus moisture	11.1	14.6	13.3	11.0
Ratio of volatile to total combustible	47.5	47.9	44.9	46.9

TESTS MADE

The tests may be divided into groups, as follows:

1. Standard tests of mixtures of coal and shale:
   - (*a*) Propagation tests.
   - (*b*) Ignition tests.
2. Standard tests of mixtures of coal and water:
   - (*a*) Propagation tests.
   - (*b*) Ignition tests.
3. Special tests of pure coal dust.

PROCEDURE IN TESTS

EXPERIMENTAL MINE

Figure 1 is a plan of the Bureau of Mines experimental mine. The coal bed is level and outcrops along a hillside. Two main entries about 10 feet wide by 6 feet high are driven back 1,300 feet; the entry on the right is called the main entry, and that on the left is called the air course. The present tests were made in the inner 350 feet of each of these entries, which are connected 50 feet from the face by a cut-through. This cut-through is the only one open, as the others have explosion-proof stoppings in them. The test zone has a concrete floor and the ribs and roof have been coated with cement applied with a cement gun.

PLAN OF TESTS

The purpose of the tests was to determine the amount of inert dust or water that must be added to the coal dust being examined to make this nonexplosive under various conditions. Whether or not an explosion will travel entirely through a zone of dust sometimes depends on the method of initiating the explosion. In a mine the most violent means of starting a dust explosion are (1) directly by

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a blown-out shot and (2) by the ignition of an explosive mixture of gas and air.

Two classes of tests are made in the experimental mine. In the first class (called ignition tests) a mixture of the coal and shale

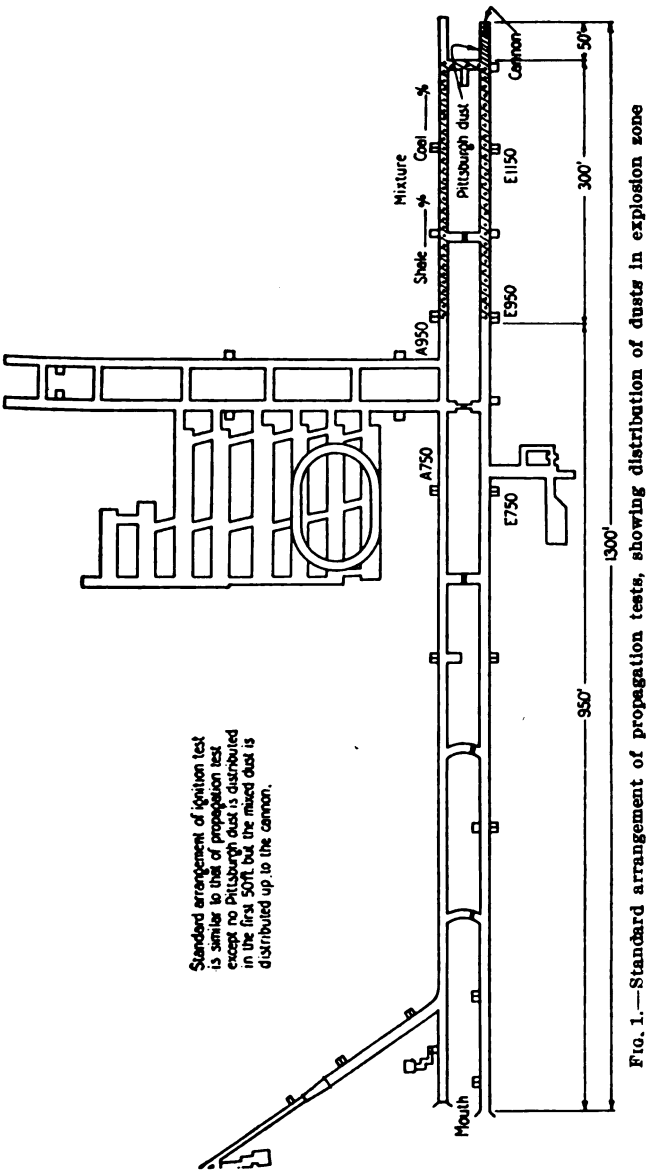

FIG. 1.—Standard arrangement of propagation tests, showing distribution of dusts in explosion zone

dusts or the wet coal dust to be tested is distributed from the face of the main entry 350 feet toward the mine mouth, and also for 50 feet through the last cut-through, and thence 300 feet toward the mouth along the parallel entry or air course. (See fig. 1.) A

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blown-out shot of 4 pounds of FFF black powder is then fired into the mixture from a cannon at the face of the entry to determine whether or not such a shot will ignite directly the dust mixture under test.

The ignition of an explosive gas mixture gives a more violent start to a dust explosion than a blown-out shot. Numerous experiments of similar character have been made in the experimental mine, with the space between the last cut-through and the face of the main entry used to confine the gas. The volume so inclosed is roughly 3,000 cubic feet; the length is 50 feet. The present series with wet dust included one such experiment. As explosive mixtures of gas and air are dangerous to handle, pulverized Pittsburgh coal dust was substituted. A 50-foot zone of this finely pulverized Pittsburgh coal dust (85 per cent through 200 mesh) distributed from the cannon to the last cut-through gives almost the same starting impulse as an explosive mixture of gas and air when ignited by a blown-out shot. This coal dust is therefore used in this zone to give a strong starting effect in the second class of tests, termed propagation tests. Outside of this zone the dust being tested is arranged as in the ignition class. Figure 1 shows the arrangement of the zones in a propagation test.

GAS

After determination of the percentages of added shale necessary to prevent ignition and propagation in the absence of gas, tests are made to ascertain the amount of shale necessary to counteract the influence of the presence in the ventilating current of 1 and of 2 per cent of gas. The gas used in such tests is natural gas, which contains some ethane and possibly other members of the paraffin group and consequently has a slightly lower explosive limit than methane. The gas is turned into the air current at the orifice of the fan about 1,300 feet from the test zone and is thoroughly mixed with the air when it reaches the test zone. Tests made from time to time with a flame safety lamp and a Burrell methane detector determine when the desired percentage of gas is present. Four samples for standard laboratory analysis are then taken at different points in the intake air. Automatic apparatus takes a sample of the gas in the 50-foot ignition zone less than 1 second before the shot is fired, so the exact percentage of gas in this zone at the instant of ignition is known later.

SIZE OF DUSTS

The size of the dust used in explosion tests is determined by the size of the road and rib dusts collected in the mines from which the coal comes. The coal is crushed so that virtually all will pass a

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20-mesh sieve. In the present tests dust having 20 per cent through 200 mesh was selected as most representative of mine conditions. Some of the coal as it came from the crusher had 20 to 22.5 per cent through 200 mesh and was used without further preparation. The remainder contained more than 22.5 per cent of 200-mesh dust and separation with an air blast and remixing of the two portions were necessary to obtain 20 per cent through 200 mesh.

The average size of the dust prepared from the four different coals follows:

Size of coal dusts used

Designation	Cumulative per cent passing through—			
	20 mesh	48 mesh	100 mesh	200 mesh
A	99.5	69.1	41.4	21.0
B	99.6	71.1	42.5	21.3
C	99.6	72.3	42.7	20.0
D	99.5	68.9	41.3	21.1

Size variations of the magnitude shown here do not affect the results of explosion tests.

PREPARATION FOR TESTS

Before each standard test with dust mixtures the test zone of the mine is thoroughly cleaned with compressed air. The dust mixtures are prepared outside the mine and are transported in closed metal cans. The mixed dust is distributed in the mine at the rate of 1 pound of coal dust per linear foot of entry, except that in the first 50 feet from the cannon 2 pounds are used per foot. The dust is equally divided between overhead cross shelves, longitudinal side shelves, and the floor. The cross shelves are omitted in the first 50 feet from the cannon, and 25 pounds of the dust are placed on the floor immediately in front of the cannon. The method of distributing the dust in the special tests of pure coal dust is given in a later section of this report that deals exclusively with such tests.

SHALE DUST USED

The shale dust mixed with the coal dusts was obtained by drying and crushing shale taken from a drift in strata about 50 feet below the level of the mine. When ready for use the shale dust was light yellow and in the tests under discussion averaged 98.6 per cent through 20 mesh, 75.5 per cent through 48 mesh, 52.9 per cent through 100 mesh, and 38.3 per cent through 200 mesh. Analyses showed an average of 1.5 per cent of moisture and 88.6 per cent of

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ash. The shale actually contains about 99 per cent of incombustible material. The difference between the sum of ash plus moisture and total incombustible is due to the presence of carbon dioxide and combined water, which appear as volatile matter in a proximate analysis.

PITTSBURGH COAL DUST USED

Pittsburgh coal dust was used in the zone from the last cut-through to the face of the main entry in propagation tests to simulate a gas explosion, as already described. This dust was prepared by crushing and pulverizing lump coal taken from No. 8 room off No. 1 left entry in the experimental mine. An average of several screen tests showed 99.5 per cent through 100 mesh and 83.7 per cent through 200 mesh. The proximate analysis of the coal dust was as follows:

Proximate analysis of Pittsburgh coal dust, per cent

Moisture	1.4
Volatile matter	38.6
Fixed carbon	55.6
Ash	4.3
Ash plus moisture	5.7
Ratio of volatile to total combustible	41.1

Comparison of this analysis with those of the Utah coals shows that the Pittsburgh coal dust contained about one-half as much ash and moisture as the Utah coals, and the ratio of volatile to total combustible was 4 to 7 per cent less. Neither difference would cause a notable change in the explosibility of pulverized dust from these coals; furthermore, the differences oppose each other as far as effect on explosibility is concerned. It may be assumed from this that the pulverized Pittsburgh coal dust had properties quite similar to those of the Utah dusts of the same size, as determined by the amount of added rock dust required to prevent propagation of an explosion.

RESULTS OF TESTS

The results of the tests are grouped according to the nature of the tests, as follows:

1. Standard tests with coal-shale mixtures:
   - (*a*) Propagation tests without gas.
   - (*b*) Propagation tests with gas.
   - (*c*) Ignition tests without gas.
2. Standard tests with coal-water mixtures:
   - (*a*) Propagation tests without gas.
   - (*b*) Ignition tests without gas.
   - (*c*) Effect of gas on coal-water mixtures.
3. Special tests with pure coal dust.

The results are recorded and discussed in the following paragraphs in accordance with this outline.

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STANDARD TESTS OF COAL-SHALE MIXTURES

Propagation tests without gas.—Eight propagation tests without gas were made with mixtures of the four coals and different proportions of shale. Table 1 gives the more important results of these tests.

TABLE 1.—*Results of standard propagation tests with coal-shale mixtures without gas*

Test No.	Coal used	Mixture as prepared		Incombustible in mixture	Pressure		Maximum flame velocity	Flame length measured from cannon		Results
		Coal	Shale		E 950	A 950		Entry	Air course	
		P. ct.	*P. ct.*	*P. ct.*	*Lbs./in.²*	*Lbs./in.²*	*Ft./sec.*	*Feet*	*Feet*	
705	*D*	45	55	60.0	1	2	400	225	400	Propagation incomplete.
704	*D*	40	60	64.4	1	1	150	150	275	Nonpropagation.
696	*C*	40	60	65.3	1	-------	210	250	400	Propagation incomplete.
709	*B*	40	60	65.8	1	3	200	350	400	Propagation.
718	*A*	40	60	64.4	1	2	190	350	400	Do.
697	*C*	35	65	69.7	1	1	21	125	125	Nonpropagation.
714	*B*	35	65	70.1	1	1	115	225	300	Do.
719	*A*	35	65	68.9	1	1	150	200	375	Do.

NOTE.—E 950 refers to station 950 in the main entry. A 950 refers to station 950 in the air course.

Table 1 shows that coal *D* was the only one tried with 55 per cent of admixed shale (test 705). The flame extended throughout the dust in the air course and to a point 75 feet from the end of the zone in the entry, showing that the mixture was unsafe.

All four coals were tested in mixtures containing 60 per cent of shale (tests 704, 696, 709, and 718). Coal *D* gave a maximum flame extension of 275 feet. Coal *C* gave propagation in the air course, but the flame stopped 100 feet short of the end of the zone in the entry. Coals *B* and *A* gave complete propagation.

Coals *C*, *B*, and *A* were tested in mixtures containing 65 per cent of shale (tests 697, 714, and 719). Propagation was not obtained in any test and the flame length ranged from 125 feet with coal *C* to 375 feet with coal *A*. The flame extension with coal *A* is longer than is desirable in a mixture that is to be considered safe. A study of the figures in Table 1 in connection with a general knowledge of experimental mine test results leads to the conclusion that mixtures which would prevent continued propagation of an explosion already started are as follows:

Mixtures that will prevent propagation

Coal	Rock dust in mixture, per cent	Incombustible in mixture, per cent
A	67	70.7
B	66	71.0
C	65	69.7
D	62	66.2

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The first three coals are almost alike in explosibility, and the last is somewhat less explosive. The total difference between the four coals is not large, and the difference between the first three is negligible, as duplicate experiments will not show closer results. The percentage of incombustible in the mixture is higher than the percentage of shale because of the ash and moisture in the coal itself.

Propagation tests with gas.—Fourteen propagation tests were made with coal-shale mixtures with gas in the air current. Table 2 gives the results of these tests.

TABLE 2.—*Results of standard propagation tests with coal-shale mixtures with gas*

Test No.	Coal used	Mixture as prepared		Incombustible in mixture	Gas	Pressure		Maximum flame velocity	Flame length measured from cannon		Results
		Coal	Shale			E 950	A 950		Entry	Air course	
		P. ct.	*P. ct.*	*P. ct.*	*P. ct.*	*Lbs./in.²*	*Lbs./in.²*	*Ft./sec.*	*Feet*	*Feet*	
722	*A*	30	70	73.3	1.3	2	2	200	350	400	Propagation.
721	*A*	25	75	77.8	1.2	1	1	110	225	375	Nonpropagation.
720	*A*	20	80	82.2	1.9	1	1	120	200	250	Do.
715	*B*	30	70	74.4	1.1	1	1	170	250	400	Propagation incomplete.
717	*B*	25	75	78.7	1.2	1	1	170	175	325	Nonpropagation.
716	*B*	20	80	82.9	2.0	1	1	125	175	325	Do.
698	*C*	30	70	74.0	.9	2	2	150	175	400	Propagation incomplete.
723	*C*	25	75	78.3	1.4	1	1	150	200	350	Nonpropagation.
699	*C*	20	80	82.7	1.7	1	1	200	150	250	Do.
701	*C*	20	80	82.7	2.0	1	1	145	150	225	Do.
706	*D*	35	65	68.9	1.0	1	2	600	350	400	Propagation.
708	*D*	30	70	73.3	1.2	1	1	160	275	400	Propagation incomplete.
724	*D*	25	75	77.8	1.4	1	1	40	125	175	Nonpropagation.
707	*D*	25	75	77.8	2.0	1	2	240	350	400	Propagation.

The results in Table 2 show that the presence of gas in the air current increases the amount of incombustible necessary in the mixed dust to prevent propagation of an explosion, a fact demonstrated by experimental mine tests a number of years ago. Careful study of all the tests before those of Utah coal has shown that the amount of additional rock dust necessary to offset gas increases with the amount of gas present. The increase progresses at such a rate that 100 per cent of incombustible would be required in the dust when 5 per cent of gas is present, irrespective of the percentage required when no gas is present. Thus, if 50 per cent of incombustible was required to prevent propagation in a mixture with no gas, each per cent of gas would require an additional 10 per cent of incombustible in order to reach 100 per cent of incombustible with 5 per cent of gas. If the original requirement without gas was 75 per cent of incombustible, then only 5 per cent additional would be required for each per cent of gas. It should be noted that 5 per cent is approximately the lower explosive limit of the natural gas used.

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Figure 2 shows graphically the behavior of the Utah dusts in the presence of gas. The diagonal lines are the limiting lines for the coals in the presence of gas. The limiting mixture with no gas varies with the kind of coal and the kind of test (ignition or propagation). This necessitates five original points for the four coals, but from these five points the lines slope upward so that they all meet at 5 per cent of gas and 100 per cent of incombustible. The section above 3 per cent of gas is shown dotted to indicate that there are no confirming tests in that range.

This relation is also shown in Table 3, in which the results given in Table 2 have been regrouped.

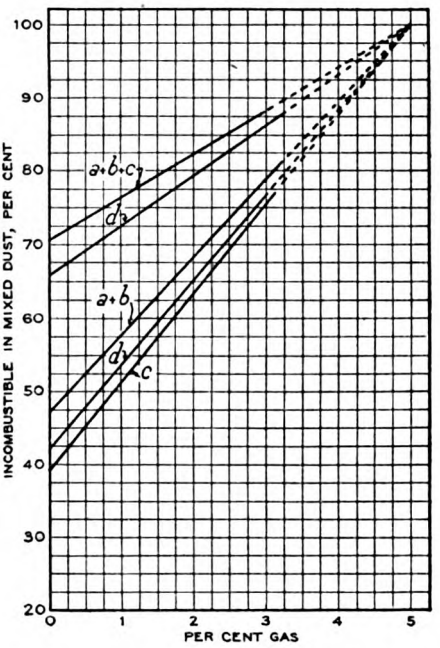

FIG. 2.—Limiting mixtures of Utah coals with various amounts of fire damp in the air. Upper lines are propagation limits; lower lines are ignition limits. Letters on lines indicate coals to which lines apply

TABLE 3.—*Comparison of computed and actual results with coal-shale mixtures with gas*

Test No.	Coal used	Gas	Calculated rock dust required	Actual rock dust present	Excess rock dust present	Results of the test
		Per cent	*Per cent*	*Per cent*	*Per cent*	
722	*A*	1.3	76	70	[1] −6	Propagation.
721	*A*	1.2	75	75	0	Nonpropagation.
720	*A*	1.9	79	80	1	Do.
715	*B*	1.1	73	70	[1] −3	Propagation incomplete.
717	*B*	1.2	74	75	1	Nonpropagation.
716	*B*	2.0	80	80	0	Do.
698	*C*	.9	71	70	[1] −1	Propagation incomplete.
723	*C*	1.4	75	75	0	Nonpropagation.
699	*C*	1.7	77	80	3	Do.
701	*C*	2.0	79	80	1	Do.
706	*D*	1.0	70	65	[1] −5	Propagation.
708	*D*	1.2	71	70	[1] −1	Propagation incomplete.
724	*D*	1.4	73	75	2	Nonpropagation.
707	*D*	2.0	77	75	[1] −2	Propagation.

[1] Deficiency.

The data given in Table 3 show that with two exceptions the actual amount of rock dust in the mixtures was within 3 per cent plus or minus that computed as necessary to prevent propagation. In five tests (720, 717, 699, 701, and 724), all of which resulted in nonpropagation, the rock dust was 1 to 3 per cent in excess. In three tests (721, 716, and 723) the percentage of rock dust computed as neces-

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sary was present, and nonpropagation again resulted; but Table 2 shows that the flame was 325 to 375 feet long in the 400-foot air-course branch, and the mixtures are very close to the dividing line.

In two tests (698 and 708) there was a 1 per cent deficiency in rock dust, and propagation was obtained through the air course but not through the entry zone. In test 707 there was a 2 per cent deficiency, and complete propagation was obtained. In test 715 the rock-dust deficiency was 3 per cent; propagation was obtained in the air course, but the flame stopped 100 feet short of the end of the zone in the entry. In tests 706 and 722 the deficiency was 5 and 6 per cent, respectively, and complete propagation was obtained in both tests.

These results show that the dust from the Utah coals followed the same general rule for the effect of gas as all coals tested before. The only marked deviation was in test 715, and this was on the side of safety, as a mixture which should have given complete propagation failed to do so.

To summarize, the effect of gas on mixtures of the four Utah coals with rock dust is such that 7 per cent more of rock dust is required for each per cent of gas with coals *A*, *B*, and *C* and 8 per cent more with coal *D*. Table 4 indicates the actual amounts necessary.

TABLE 4.—*Percentage of rock dust in safe mixtures, without and with gas*

Coal	Rock dust in safe mixture when the gas in the air current is—		
	0 per cent	1 per cent	2 per cent
A	67	74	81
B	66	73	80
C	65	72	79
D	62	70	78

These figures refer to the percentage of rock dust in the total dust present. The percentage of incombustible material in the dust will be 3 to 4 per cent higher because of the ash and moisture in the coal itself. The rock dust is assumed to contain no appreciable amount of combustible material.

TABLE 5.—*Ignition tests with coal-shale mixtures without gas*

Test No.	Coal used	Mixture as prepared		Incombustible in mixture	Pressure		Maximum flame velocity	Flame length measured from cannon		Results
		Coal	Shale		E 950	A 950		Entry	Air course	
		Per cent	*Per cent*	*Per cent*	*Lbs./in.²*	*Lbs./in.²*	*Ft./sec.*	*Feet*	*Feet*	
730	*D*	75	25	33.3	3	3	385	350	400	Ignition.
726	*C*	70	30	39.3	0.5	0.5	60	100	175	Nonignition.
727	*B*	70	30	40.2	4	4	400	350	400	Ignition.
728	*A*	70	30	37.8	2	1	250	350	400	Do.
725	*D*	65	35	42.2	.5	.5	30	75	125	Nonignition.
729	*B*	65	35	44.5	1	1	125	350	400	Ignition.
710	*B*	60	40	48.8	.5	.5	20	75	175	Nonignition.

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Ignition tests without gas.—Seven ignition tests were made with coal-shale mixtures without gas. Table 5 gives the results of these tests.

The Table 5 results show that a smaller amount of admixed rock dust is necessary to prevent ignition than to prevent propagation. The ignition test is less severe than the propagation test. The latter determines whether the mixed dust will continue to propagate an explosion already well started, whereas the ignition test determines the ability of the mixed dust to ignite and develop an explosion from a blown-out shot of 4 pounds of black powder. Thirty per cent of shale in the mixture prevented ignition with coal *C*, 35 per cent prevented ignition with coal *D*, and 40 per cent prevented ignition with coal *B*. The mixture was not determined with coal *A*, but 40 per cent of shale would probably be enough.

These results show that coals *A* and *B* require the most shale to prevent ignition, as they did to prevent propagation. Coal *D* requires more shale in the ignition test than does coal *C*, the reverse of the conditions determined in the propagation tests. The differences between the coals are more marked in the ignition tests, but it is also true that the limiting mixtures were not determined as closely, and additional ignition tests might change the amount of shale necessary with coals *A* and *D* by amounts not in excess of 5 per cent. The values given above are on the safe side, however.

Effect of gas in ignition tests.—When gas is used in the air current in ignition tests the explosibility of the dust is increased, as in the propagation tests. The increase is such that 100 per cent of rock dust would be reached with 5 per cent of gas. No ignition tests with gas were made with Utah coals, but from the general results of experimental mine tests it is safe to say that under ignition-test conditions coals *A* and *B* would require 12 per cent, coal *D* 13 per cent, and coal *C* 14 per cent more of rock dust in the mixture for each per cent of gas in the air current.

TABLE 6.—*Percentage of rock dust and total incombustible in mixtures which will not ignite from a blown-out shot of 4 pounds of black blasting powder*

Coal	Composition of safe mixture when gas is—					
	0 per cent		1 per cent		2 per cent	
	Rock dust	Incombustible	Rock dust	Incombustible	Rock dust	Incombustible
A	40	47	52	57	64	68
B	40	49	52	59	64	69
C	30	39	44	51	58	64
D	35	42	48	54	61	65

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Table 6 gives the amounts of rock dust that must be added to prevent ignition. The corresponding total incombustible content of the mixed dust is also given, as the incombustible in the coal becomes a larger and more important part of the total as the proportion of rock dust added is decreased.

TESTS OF COAL-WATER MIXTURES

Maximum amount of water absorbed by coal dust.—The amount of admixed water that coal dust will retain is limited and depends on the size of the dust. If a larger amount of water is used, the excess will settle down through the dust and if unconfined will drain away. To determine the maximum amount of water that could be retained when mixed with Utah coals a test was made of coal *C*, the size of which is specified in the tabular statement on page 5. A uniform mixture containing 24 per cent of water was prepared and placed in a metal can. Sampling and determinations of moisture were carried on for 5 days. The moisture content at the top of the can dropped in 24 hours to about 20 per cent. It was therefore concluded that this percentage of water was the maximum amount that would be held by Utah dust of that size after watering. Finer dust might hold a little more and coarser dust less. This is independent of the further loss of moisture in the mine from the drying effect of the ventilating current.

Propagation tests without gas.—Ten propagation tests were made of coal-water mixtures without gas. Nine were standard tests with a blown-out shot of black powder and pulverized Pittsburgh coal dust in the zone between the last cut-through and the face of the main entry. An explosive gas mixture confined in the dead end by a paper diaphragm was used to originate the explosion in the remaining test. The gas was ignited by firing three black-powder igniters at the face. Table 7 gives the results of the tests.

TABLE 7.—*Results of propagation tests with coal-water mixtures without gas*

Test No.	Coal used	Mixture as prepared		Moisture in dust as tested	Pressure		Maximum flame velocity	Flame length measured from cannon		Results
		Coal	Water		E 950	A 950		Entry	Air course	
		Per cent	*Per cent*	*Per cent*	*Lbs./in.²*	*Lbs./in.²*	*Ft./sec.*	*Feet*	*Feet*	
732	*B*	84	16	16.7	13	13	530	350	400	Propagation.
746	*C*	84	16	16.0	9	11	1,800	350	400	Do.
737	*D*	84	16	19.8	4	4	800	350	400	Do.
745	*A*	80	20	21.5	.5	1	80	150	250	Nonpropagation.
733	*B*	80	20	20.4	.5	.5	100	150	200	Do.
747	*B*	80	20	21.1	2	2	700	350	400	Propagation.
750	*C*	80	20	21.6	1	1	120	150	300	Nonpropagation.
755 [1]	*C*	80	20	21.0	15	14	900	350	400	Propagation.
741	*D*	80	20	23.0	2	3	500	350	400	Do.
749	*D*	78	22	25.6	.5	1	40	125	150	Nonpropagation.

[1] Gas ignition in test 755

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In considering the tests with water mixtures the fundamental difference between the action of water and rock dust should be kept in mind. Rock dust is effective because it produces an incombustible dust cloud. Water is effective because it prevents the formation of a dust cloud. If the water present is not enough to prevent formation of a dust cloud, it is not effective.

The reader will note that with coals *A* and *D* the moisture in the dust tested as determined by analysis was 2 to 4 per cent higher than the amount added. These coals contain 5 to 6 per cent of inherent moisture, which appears with the added water in the analysis.

Coals *B*, *C*, and *D* were tested in mixtures containing 16 per cent of added water and propagation was invariably obtained (tests 732, 746, and 737). When 20 per cent of water was used, coals *A* and *B* failed to give propagation (tests 745 and 733). A second trial was made with coal *B* (test 747), and complete propagation was obtained. A mixture of coal *C* containing 20 per cent of added water failed to give propagation under standard conditions (test 750). In test 755 an explosive gas mixture was used to ignite a mixture of this coal that contained 20 per cent of added water. A rapid, violent explosion resulted. An explosive gas mixture ignited at the face gives a heavy concussion and has greater dust-raising power than the blown-out shot from the cannon. This test proves that when dust containing 20 per cent of water is raised in the air it will propagate an explosion, and an ignition of gas under certain conditions will suffice both to raise and to ignite the wet dust.

Coal *D* was tested in a mixture containing 20 per cent of added water (test 741) and gave complete propagation. It was tested again with 22 per cent of water (test 749) and failed to give propagation.

The conclusion must be drawn from these tests that water can not be relied on as a general preventive of coal-dust explosions. Dust that contained 20 per cent of moisture propagated an explosion in three out of six trials, and when gas was used as a primary source of ignition the explosion was violent and destructive. Wet dust is explosive, and only needs to be raised in the air to become as much of a menace as dry dust. Analyses of the samples taken in the single test with 22 per cent of added water showed that the dust was saturated and the mixture somewhat unstable. It is doubtful if this quantity of water could be retained for any great length of time.

Although the above tests show that general watering in entries will not prevent the spread of a well-developed explosion, the use of water at the face and on mining machines may readily prevent the initiation of an explosion from sources other than an ignition of gas. Water is effective in preventing the ignition of coal dust from weak sources of ignition, as the tests described in the next paragraph show.

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Ignition tests without gas.—Six ignition tests were made of coal-water mixtures without gas. Table 8 gives the results of these tests.

TABLE 8.—*Results of ignition tests with coal-water mixtures without gas*

Test No.	Coal used	Mixture as prepared		Moisture in dust as tested	Pressure		Maximum flame velocity	Flame length measured from cannon		Result
		Coal	Water		E 950	A 950		Entry	Air course	
		Per cent	*Per cent*	*Per cent*	*Lbs./in.²*	*Lbs./in.²*	*Ft./sec.*	*Feet*	*Feet*	
711	*B*	92	8	10.8	27	28	770	350	400	Ignition.
754	*C*	92	8	10.4	.5	.5	80	100	200	Nonignition.
752	*C*	90	10	12.9	1	1		100	125	Do.
738	*D*	90	10	14.3	2	2	350	350	400	Ignition.
748	*D*	88	12	17.1	.5	.5	50	100	175	Nonignition.
736	*B*	88	12	13.4	.5	.5		75	125	Do.

Ignition tests were made of mixtures of coals *B* and *C* containing 8 per cent of added water. The total moisture in the dust was 10.8 and 10.4 per cent, respectively. Ignition was not obtained in test 754 with coal *C*, but a strong explosion developed in test 711 with coal *B*. Coal *C* had already been tried in test 752 with 10 per cent of added water, and ignition had not been obtained. Coal *D* gave ignition in test 738 with 10 per cent of added water (14.3 per cent of total moisture), but failed to do so in test 748 with 12 per cent of added water. The total moisture content of the dust was 17.1 per cent in this test. Coal *B* also failed to give ignition in test 736 with 12 per cent of added water, that made the total moisture content of the mixed dust 13.4 per cent.

In general, 12 per cent of added moisture might be considered enough to prevent ignition of the wet dust from a blown-out shot of 4 pounds of black powder. This amount is probably close to the danger line for coal *D*, and a determination was not made with coal *A*. It would therefore be best to consider 12 per cent as a minimum value, except with coal *C*, which was less sensitive to ignition when wet than the other two coals tested. Dust with this amount of water is nevertheless definitely explosive when raised in a cloud, as the propagation tests with wet dust showed. All that is necessary is to provide a concussion powerful enough to raise the dust cloud and a flame to ignite it when raised. The blown-out shot used in the present tests was not strong enough to raise and ignite the cloud, but the violent concussion that accompanied the ignition at the face of a small body of an explosive gas-air mixture doubtless would suffice to raise a dust cloud that would ignite and propagate a disastrous explosion.

Effect of gas on coal-water mixtures.—The presence of gas in the air current was expected to increase the explosibility of wet dusts

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as it did that of dry dust mixtures. The magnitude of the effect was doubtful, however, for if wetting the dust prevented any dust cloud from forming, the addition of gas would make little difference until the lower explosive limit of the gas itself was approached. On the other hand, if wetting the dust merely reduced the density of the dust cloud below that necessary for propagation of flame, the presence of gas in the air might serve to overcome this reduction.

Two propagation and three ignition tests were made with coal-water mixtures with gas in the air current. The number was limited by exhaustion of the supply of coal sent for test. Table 9 gives the results of these tests.

TABLE 9.—*Results of standard tests of coal-water mixtures with gas*

Test No.	Coal used	Mixture as prepared		Moisture in dust as tested	Gas	Pressure		Maximum flame velocity	Flame length measured from cannon		Result
		Coal	Water			E 950	A 950		Entry	Air course	
Propagation tests:		*Per cent*	*Per cent*	*Per cent*	*Per cent*	*Lbs./in.²*	*Lbs./in.²*	*Ft./sec.*	*Feet*	*Feet*	
734	*B*	80	20	21.0	1.5	6	7	530	350	400	Propagation.
735	*B*	76	24	21.9	1.5	1	1	120	350	400	Do.
Ignition tests:											
756	*C*	90	10	12.7	0.7	5	5	500	350	400	Ignition.
757	*C*	84	16	17.6	1.1	.5	.5	.....	75	100	Nonignition.
758	*C*	84	16	18.0	2.1	.5	.5	100	100	100	Do.

Test 734, of a mixture of coal *B* containing 20 per cent of water, has little meaning, as propagation was obtained with a similar mixture without gas in a later test. (See Table 7, test 747.) A mixture containing 24 per cent of added water was prepared for test 735, but when the dust was distributed and samples were taken there was only an average of 21.9 per cent of total moisture in the dust. Fourteen hours passed between the preparation and the distribution of the dust, and the excess water had drained away. Conditions as to moisture and gas were then the same as in test 734, and propagation was obtained.

In test 756 a mixture of coal *C* containing 10 per cent of added water and 12.7 per cent of total moisture was tried with 0.7 per cent of gas, and ignition was obtained. This mixture had failed to give ignition with no gas in test 752 (see Table 8). The added water was increased to 16 per cent for tests 757 and 758, with 1.1 and 2.1 per cent of gas, respectively. Ignition was not obtained in either test.

These results show that in the ignition tests additional water had to be used to offset the effect of gas. Six per cent more of water was

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enough to offset 2 per cent of gas with coal *C*, the only one tried. With tests that gave propagation, the entire amount of water the dust will hold sometimes fails as a preventive when no gas is present, and nothing further can be done when gas is present.

SPECIAL TESTS WITH PURE COAL DUST

Purpose of tests.—In the foregoing tests the mixture of coal and shale dusts or wet coal dust was evenly distributed throughout the test zone. One-third of the dust was placed on overhead cross shelves, the arrangement best calculated to produce a dense and uniform dust cloud when the cannon is fired. These conditions are not like those in the Utah mines in two respects: (1) Supporting the roof of entries there are few or no crossbars which could serve to collect dust and give a distribution similar to that obtained with the cross shelves in the experimental mine; (2) in haulage entries there is considerable spillage, and a strip as wide as the cars is covered with nearly pure coal dust mixed with fallen lumps. This strip is wet to keep the dust from spreading and to render it inert.

Seven tests were made with special distribution and mixtures of dust of coal *A* in order to simulate as closely as possible haulageway conditions in the mines from which the present samples were obtained.

Arrangement of dust.—All the special tests were propagation tests, with the standard blown-out shot of 4 pounds and pulverized Pittsburgh coal dust distributed from the last cut-through to the face of the main entry. The dust being tested was distributed in the last cut-through and toward the mouth, on both entry and air course, to the ends of the test zone.

Pure coal dust or coal dust mixed with water was distributed, at the rate of 1 pound of coal dust per linear foot, on the floor only in a strip 5 feet wide along the center of the entry. Mixed coal and shale dust was distributed on the remainder of the floor and on the side shelves only. The mixed dust was distributed at the rate of 1⅔ pounds per linear foot, and 25 per cent of the total was on the side shelves. No dust was placed on the cross shelves. The condition was thus similar to an entry in which the floor and ribs had been rock-dusted and later contaminated by dust spilled from the moving cars. The purpose was to test the most dangerous conditions; therefore mixtures containing 30 to 40 per cent of coal dust were used on the sides of the floor and the side shelves instead of pure rock dust. Gas was not used in these tests.

Results of tests.—Table 10 gives the results of the seven tests.

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TABLE 10.—*Results of special propagation tests with coal A*

Test No.	Coal dust in 5-foot strip			Mixed dust on floor and side shelves			Pressure		Maximum flame velocity	Flame length measured from cannon		Results
	Coal	Water	Total moisture	Coal	Shale	Incombustible	E 950	A 950		Entry	Air course	
	P. ct.	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*Lbs./in.²*	*Lbs./in.²*	*Ft./sec.*	*Feet*	*Feet*	
731	100	0	4.6	30	70	73.3	1	1	280	350	400	Propagation.
739	100	0	5.2	[1] 30	70	73.3	2	2	300	350	400	Do.
740	92	8	11.4	30	70	73.3	1	2	300	350	400	Do.
742	90	10	13.3	30	70	73.3	.....	.....	120	125	225	Nonpropagation.
744	90	10	14.6	40	60	64.4	1	1	130	250	350	Do.
743	90	10	12.8	([2])	([2])	.....	1	1	40	125	225	Do.
751	92	8	9.9	([2])	([2])	.....	1	1	150	250	350	Do.

[1] The coal-shale mixture in test 739, was the same as in test 731, but the quantity was doubled.
[2] None used.

Before considering the results of the special tests the reader should note that the distribution of dust influences explosibility, largely because distribution affects the ease with which a dust cloud can be formed. A smaller amount of added shale dust is needed to prevent propagation when there is no dust on the cross shelves.

In the first four special tests the mixed dust used contained 70 per cent of shale. This mixture would not propagate an explosion if loaded in the regular manner, and if distributed only on the side shelves and on the sides of the floor it would give a wider margin of safety. In the first test (731) there was pure coal dust in the center strip on the floor, and the explosion traveled along this strip to the ends of the test zone. In the next test (739) the quantity of mixed dust was doubled, but its composition was unchanged. The result was the same as in the first test.

These two tests indicated that the shale in the mixed dust at the sides would not extinguish an explosion traveling through the pure coal dust in the center of the entry. The reason is probably that the mixed dust is not carried out to the center of the entry in a large enough quantity to have any value. Although there are eddy currents in the moving column of air and dust ahead of the flame, the movement in the center is mainly longitudinal.

The next step was to treat the pure coal dust with water without changing the mixed dust. Eight per cent of water was added in test 740, and complete propagation was again obtained. Ten per cent of added water was used in test 742, and the explosion died out after traveling 225 feet from the cannon. The moisture in this dust totaled 13.3 per cent.

After conditions which failed to give propagation had been found, the effect of increasing the percentage of coal in the mixed dust was determined. In test 744 the wet dust contained 10 per cent of added water, and the mixed dust contained 40 per cent of coal. Propaga-

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tion was not obtained, but the flame extended 350 feet from the cannon. This mixed dust would be definitely explosive under standard test conditions, but when distributed as in this test and used alone it would be close to the border line of explosibility and might fail to propagate.

The conclusion drawn from the foregoing tests was that the pure or wet dust in the center of the floor was measurably independent of the mixed dust on the sides during an explosion. Two additional tests were made to test this conclusion. In test 743, pure coal dust with 10 per cent of water added was distributed and no mixed dust was used. The flame extension was the same as in test 742, in which mixed dust containing 70 per cent of shale was also used. In the last test (751) coal dust with 8 per cent of added water was used without mixed dust. Propagation was not obtained, but the flame reached a point 50 feet from the end of the air-course zone. Propagation had been obtained in test 740 with a combination of similar wet dust and mixed dust containing 70 per cent of shale. As the mixed dust is definitely nonexplosive, the difference in the results in tests 740 and 751 is ascribed to differences in the formation of the dust cloud in the two tests. The variation in flame lengths in tests 742, 743, and 744 is probably due to the same cause, for it is much more difficult to produce and reproduce a uniform dust cloud with wet dust than with dry dust.

The conclusion then is that the strip of coal dust in the center of the floor must be treated without reference to the sides and ribs. The dust on the ribs and roof and sides of the floor should contain the amount of incombustible material determined by the propagation tests of mixed dusts, while the pure coal strip on the floor should contain not less than 10 and preferably 12 per cent of added water. The total moisture content in this strip will then be 13 to 15 per cent with the four coals. It is not safe to depend in any way on the decreased explosibility caused by the absence of overhead timbers and hence the absence of timber dust, because of its uncertain application to operating conditions.

COMPARISON OF THE EXPLOSIBILITY OF UTAH AND PITTSBURGH COAL DUSTS

For a number of reasons Pittsburgh coal dust has been taken as the standard of explosibility in work at the experimental mine. The mine was developed in the Pittsburgh bed and the coal is always available in quantity. A thorough study of the properties of the coal has been made and results of the tests have been reported in Bulletins 167 [2] and 268.[3] Pittsburgh coal dust is also one of the most

[2] Rice, G. S., Jones, L. M., Egy, W. L., and Greenwald, H. P., Coal-Dust Explosion Tests in the Experimental Mine, 1913 to 1918, Inclusive: Bull. 167, Bureau of Mines, 1922, 639 pp.

[3] Rice, G. S., Paul, J. W., and Greenwald, H. P., Coal-Dust Explosion Tests in the Experimental Mine, 1919 to 1924, Inclusive: Bull. 268, Bureau of Mines (in press).

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explosive dusts found in the mines of the United States. To compare the results obtained with Pittsburgh and with Utah coal dusts is therefore a matter of interest.

Explosion tests have shown that 63 per cent of incombustible is required in a mixture of 20-mesh (20 per cent 200-mesh) Pittsburgh coal dust and rock dust to prevent propagation of an explosion through it. The four Utah coals (*A*, *B*, *C*, and *D*) required 71, 71, 70, and 66 per cent of incombustible, respectively, to prevent propagation through similar 20-mesh dust mixtures, and all are consequently more explosive than Pittsburgh coal dust. If the explosibility of Pittsburgh dust is taken as 100, that of the four Utah dusts is 113, 113, 111, and 105, respectively. The only coal previously tested that needed more than 66 per cent of incombustible was a subbituminous coal from Montana, which required 69 per cent, and whose explosibility would be designated by the number 110 if the explosibility of Pittsburgh dust were taken as 100. Coals *A*, *B*, and *C* are thus the most explosive ever tested at the experimental mine.

The high degree of explosibility of the pure coal dust is not in any way offset by the natural conditions surrounding the formation of mine dust. As noted in the preface, the coal bed carries few impurities and there is little admixture of inert particles from the floor or roof, hence the mine dust is always pure coal dust. This is in contrast with mines in the eastern and central coal fields, where incombustible material from clay or shale floor, roof, or partings may become mixed with the fine coal, resulting in a considerable increase in the incombustible content of the mine dust over that in the coal dust.

Some of the Utah coals carry resin in flakes that can be picked out of the coal mass with ease. This resin, when isolated, is highly inflammable, and it was thought that presence of the resin might render a coal more explosive. Coal *D*, which carried a considerable amount of this resin, was selected, but the tests show that coal *D* was the least explosive of the four. The explanation is that, although the resin is readily seen because of its color and luster, the amount present in proportion to the whole mass of the coal is too small to affect explosibility.

SUMMARY

The results of the tests of the four Utah coals and the conclusions drawn therefrom may be summarized as follows:

1. The four coals, *A*, *B*, *C*, and *D*, required 67, 66, 65, and 62 per cent, respectively, of rock dust in a mixture to prevent the continuance through them of a developed explosion in the absence of gas. The total incombustible content of these mixtures was 71, 71, 70, and 66 per cent, respectively, which includes the inherent moisture and ash of the coal.

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2. Additional rock dust must be present when there is gas in the air current. For each per cent of gas present up to 5 per cent, there must be 7 per cent of additional rock dust with coals *A*, *B*, and *C*, and 8 per cent with coal *D*, to prevent continued propagation of a well-developed explosion, such as might originate from a gas explosion at the face of an entry.

3. It follows that with 1 per cent of gas present the amount of shale dust present must be 74, 73, 72, and 70 per cent, respectively, for coals *A*, *B*, *C*, and *D*.

4. When a weaker source of ignition, such as a blown-out shot of 4 pounds of black blasting powder, is used, a smaller amount of rock dust is required in the mixture.

5. Preventing direct ignition of the mixed dust from a blown-out shot of 4 pounds of black blasting powder in the absence of gas required 30 per cent of rock dust in the mixture of coal *C*, 35 per cent with coal *D*, and 40 per cent with coal *B*. A determination was not made with coal *A*, but 40 per cent of rock dust would probably be enough.

6. For each per cent of gas in the air current an additional 12 per cent of rock dust for coals *A* and *B*, 13 per cent for coal *D*, and 14 per cent for coal *C* will be required to prevent direct ignition of the dust from a blown-out shot of 4 pounds of black blasting powder.

7. There is a maximum amount of water that coal dust will absorb when wet; it was found to be 20 per cent with coal *C*, and this figure can be used for all four coals.

8. Mixtures containing 20 per cent of added water propagated explosions in three of six trials. When the dust was ignited by an explosion of gas, the coal-dust explosion was violent and destructive.

9. Twelve per cent of added water prevented the ignition from a blown-out shot of 4 pounds of black blasting powder, in the absence of gas, with all the coals except coal *A*, for which no such determination was made.

10. The number of gas tests with wet dusts was small, but a mixture of coal *C* containing 16 per cent of added water failed to ignite with 2 per cent of gas in the air current.

11. When there is a strip of more or less pure coal dust on the floor in the center of the entry (as from spillage) this strip must receive special consideration. Well rock-dusted ribs will not take care of it, and unless rock dust can be placed on overhead timbers or projections extending entirely across the entry the center strip must be separately treated.

12. The center strip required a minimum of 10 per cent of added water in the few tests made and the rock-dusted parts should be kept above the limit determined in the standard tests.

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